Evaluation of Emissions and Performance of NJ Transit Diesel Locomotives with B20 Biodiesel Blends

Research Project Summary

ABSTRACT

In an effort to explore the feasibility of reducing its carbon footprint, New Jersey TRANSIT partnered with the New Jersey Department of Environmental Protection (NJDEP) in research on the use of biodiesel in its commuter train locomotives. This research was conducted by Rowan University under contract to the NJDEP. This report summarizes the research, which evaluated the exhaust emissions and performance characteristics of several 20% biodiesel-petroleum diesel blends (B20) in diesel locomotives as compared to several petroleum diesel blends. In total, testing was performed with eight fuel blends, four of which were petroleum diesel blends, and four of which were biodiesel-petroleum diesel blends. The fuels tested were: #2 diesel summer blend, #2 diesel winter blend, ultra low sulfur diesel (ULSD) summer blend, ULSD winter blend, and B20 blends with each of these fuels. Tests were performed on two different diesel locomotive types, which are representative of New Jersey TRANSIT's current in-service fleet, to determine the differences in performance and emissions between older and newer locomotive engines when operating on biodiesel blends. The research results demonstrate that the performance of both types of locomotives was not negatively affected when B20 was utilized. The summer and winter B20 blends tests for both engines resulted in a decrease in carbon dioxide (CO2) exhaust emissions. However, B20 winter blend tests resulted in an increase in hydrocarbon (HC) emissions in both newer and older locomotives. Summer B20 blends resulted in a decrease in all of the measured pollutants in newer locomotives, but an increase in NOx and HC in older locomotives. Increases in NOx and HC cause increases in concentrations of ground-level ozone, and may increase local air toxics impacts.

INTRODUCTION

Biodiesel is a renewable alternative fuel that can be produced from oils and fats (i.e. soybean oil, used vegetable oils, animal fats and tallow) and potentially algae via a chemical reaction called trans-esterification. Neat biodiesel (B100) contains 88-95% as much energy as petroleum diesel fuel; however, biodiesel can improve diesel lubricity, which prevents wear on contacting metal surfaces. In addition, biodiesel can raise cetane values (i.e., reducing ignition delay of the fuel). Moreover, the alcohol component of biodiesel contains oxygen, which helps to complete the combustion of the fuel, potentially reducing air pollutants such as particulates, carbon monoxide and hydrocarbons. Biodiesel contains practically no sulfur, so it can help to reduce emissions of sulfur oxides.

Biofuels are generally categorized, based upon their feedstock source, as either "first generation", "second generation", or "third generation". If produced from soybean oil, biodiesel is considered a first generation biofuel. Second generation and third generation biofuels are defined as being produced from waste oil, and algae respectively. First generation biodiesel was used in this analysis because it was the biofuel that was commercially available at the time the research was conducted.

The NJ TRANSIT diesel locomotive fleet currently consumes approximately 12.3 million gallons of petroleum diesel per year. Because of the volatility of oil prices, concerns about potential disruptions in supply, and environmental considerations, NJ TRANSIT wanted to evaluate the feasibility of substituting a portion of their petroleum diesel with biodiesel. Since biodiesel is typically blended at 20% with petroleum diesel (such formulation is designated as B20), a full deployment of B20 by NJ TRANSIT would reduce NJ TRANSIT's fossil fuel consumption by nearly 2.5 million gallons per year. Such a full-scale deployment could potentially have substantial positive impact on the environment by reducing NJ TRANSIT's carbon footprint as well as by reducing other air pollutants. Therefore, the purpose of this investigation was to assess the use of biodiesel-petroleum diesel blends in the NJ TRANSIT diesel locomotives, and measure their performance characteristics.

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Although new and remanufactured locomotive engines must meet national emissions requirements, which will be phased in beginning 2010, the existing diesel locomotive engines continue to be significant contributors to air pollution in many of our nation's most populated areas. Specifically, they continue to emit large amounts of oxides of nitrogen (NOx), particulate matter (PM), carbon monoxide (CO) and unburned hydrocarbons (HC), all of which have been shown to contribute to serious health problems. In 2004, as part of the Clean Air Nonroad Diesel Rule, the USEPA finalized requirements for nonroad diesel fuel that will decrease the allowable levels of sulfur in fuel used in locomotives by 99%. However, at the time of the study, NJ TRANSIT maintained an inventory of 122 diesel locomotives, the majority of which are approximately 30 years old. These older engines are not covered by the USEPA standards. Rebuilding these engines would trigger a requirement that they be upgraded to meet both of the standards, but this would be very costly. Moreover, retrofitting the older locomotive engines with exhaust after-treatment technology (i.e. particulate filters) would also be costly. Due to the high cost of engine rebuilds and retrofits, NJ TRANSIT chose to investigate the possibility of a fuel strategy instead. In 2007, a grant was awarded from the NJDEP to Rowan University to perform an experimental study on exhaust emissions of NJ TRANSIT diesel locomotives operating on biodiesel blends with the following objectives:

- To determine the emissions benefits and drawbacks of using biodiesel in the NJ TRANSIT locomotive fleet
- To determine if there are any potential difficulties in using biodiesel, such as reduced power and/or storage and handling difficulties.

TEST PLAN, FUELS, INSTRUMENTATION AND EQUIPMENT

The investigation was performed at the NJ TRANSIT Meadows Maintenance Complex. Tests were performed on two different types of diesel locomotive engines to assess performance and emissions in both newer and older locomotives when operating with various petroleum blends and biodiesel-petroleum diesel blends. Both engines were operated statically (i.e. while standing still) under engine performance conditions similar to those that exist when the locomotive is moving, over the full test matrix of the eight fuels shown below.

Fuel blends used for tests:

Petroleum Diesel	**Biodiesel Blends**
#2 Summer Blend (100% #2 diesel, 500 ppm sulfur)	B20-Summer (20% biodiesel, 80% #2 diesel)
#2 Winter Blend (70% #2 diesel, 30% kerosene,)	B20-Winter (20% biodiesel, 24% #2 diesel, 56% kerosene)
ULSD Summer (100% diesel, <15 ppm sulfur)	B20-ULSD Summer (20% biodiesel, 80% ULSD)
ULSD Winter (60% ULSD, 40% kerosene,)	B20-ULSD Winter (20% biodiesel, 24% ULSD, 56% kerosene)

The GP40FH-2 is an older locomotive built in 1972 with a 3000 HP turbocharged EMD 16-645 engine. The PL42AC is a newer locomotive manufactured in 2005 with a 3650 HP turbocharged EMD 16-710 engine.

A Semtech-D/Sensors Inc. mobile emissions analyzer was used for the gaseous emissions measurements during the tests. The instantaneous engine horsepower calculations were performed by measuring the alternator voltage and current. The instantaneous fuel flow rate data, opacity data, load box data and additional temperature data were acquired using an Agilent 3470A data logger. The opacity of the locomotive exhaust plume was quantified using a Wager 6500RR Railroad Opacity Meter. Opacity is an indicator of the particulate concentration in the exhaust, although there is not a direct correlation.

Each test was conducted according to the test protocol summarized in Table B-124-1 of the Federal rule governing testing of locomotives (§92.124 of CFR Title 40, Part 92). The test protocol is designed to simulate real-life operating conditions of commuter trains, including acceleration and deceleration between train stations, and idling during station stops. Therefore, the test procedure entails operating the locomotive for a specified period of time in each of 9 gear settings (or "notches"), while the power from the main alternator is dissipated at a load box. The locomotive is operated in each of the first 8 notches (from idle to notch 7) for 6 minutes and in notch 8 for 15 minutes. During each of the test modes, exhaust gas concentrations, exhaust opacity, fuel flow rate, fuel temperature, alternator voltage and alternator current data are acquired..[a]

[a] For a full discussion of the test protocol, including the procedures for calculating emission rates and engine horsepower, see the full report, *Rowan University, Evaluation of Emissions and Performance of NJ TRANSIT Diesel Locomotives with B20 Biodiesel Blends. Final Report: December 10, 2009.*

TEST RESULTS AND DISCUSSION

Emission tests

Tables one and two below summarize the results of the emission tests, with a detailed discussion of the findings following. Mass emissions are based on a weighted average of all notch settings using weighting factors developed from NJ TRANSIT notch data. Values for carbon dioxide (CO_2), oxides of nitrogen (NOx), total unburned hydrocarbons (HC), and carbon monoxide (CO) represent measured emissions. Percent change represents the difference in emission level between that of a baseline fuel (i.e. a fuel commonly used by NJ TRANSIT in a particular engine type) and that of another tested fuel. Baseline fuels for the GP40FH-2 engine were #2 summer blend and #2 winter blend. Baseline fuels for the PL42AC engines were LSD summer and LSD winter. To provide additional information to the state regarding the effect of B20 biodiesel blends on greenhouse gas emissions, the investigators calculated "Estimated Soy Biodiesel Greenhouse CO_2", which represents CO_2 emissions for each of the B20 blends based on a life cycle analysis.[b]

Table 1. Summary of emissions measurements from GP40FH-2 locomotive.[c]

	CO_2		NOx		HC		CO		Estimated Soy Biodiesel Greenhouse CO_2	
Fuel	kg/hr	% change	g/hr	% change	g/hr	% change	g/hr	% change	kg/hr	% change
#2 Summer	1050.3	---	13940	----	486.4	----	2631	----	1050.3	----
ULSD-Summer	1004.9	-4.3%	15787	13.2%	524.1	7.8%	1722	-34.6%	1004.9	-4.3%
B20-Summer	1029.5	-2.0%	14944	7.2%	----	----	2466	-6.3%	980.1	-6.7%
ULSD-B20-Summer	1036.5	-1.3%	16023	14.9%	559.6	15.1%	1498	-43.1%	986.7	-6.0%
#2 Winter	1012.4	----	15453	----	540.1	----	2382	----	1012.4	----
ULSD Winter	973.1	-3.9%	13868	-10.3%	560.0	3.7%	2741	15.0%	973.1	-3.9%
B20-Winter	1014.2	0.2%	14576	-5.7%	566.9	5.0%	2091	-12.2%	965.6	-4.6%
ULSD-B20-Winter	968.5	-4.3%	13974	-9.6%	564.4	4.5%	3330	39.8%	922.0	-8.9%

Table 2. Summary of emissions measurements from PL42AC locomotive.

	CO_2		NOx		HC		CO		Estimated Soy Biodiesel Greenhouse CO_2	
Fuel	kg/hr	% change	g/hr	change	g/hr	% change	g/hr	% change	kg/hr	% change
LSD Summer	2371.9	----	27336	----	1085.4	----	7755	----	2371.9	----
LSD-B20-Summer	2046.3	-13.7%	23086	-15.5%	1011.6	-6.8%	5640	-27.3%	1935.8	-18.4%
LSD Winter	1637.5	----	18351	----	558.4	----	5620	----	1637.5	----
ULSD Winter	1288.7	-21.3%	13877	-24.4%	543.5	-2.7%	3393	-39.6%	1288.7	-21.3%
LSD-B20-Winter	1371.7	-16.2%	15086	-17.8%	720.6	29.1%	2760	-50.9%	1297.6	-20.8%
ULSD-B20-Winter	1513.9	-7.5%	15764	-14.1%	624.9	11.9%	----	----	1259.6	-23.1%

[b] Life cycle analysis is "cradle-to-grave" (or "field-to-wheels") evaluation of the environmental impacts of a product from its manufacture to final disposal, and includes factors such as energy and raw materials required for its manufacture, pollution caused by its use, and method of disposal. Life cycle analysis of a biofuels takes into account direct and indirect land use effects.

[c] The missing data in tables one and two are a result of equipment failure during the tests.

CO_2 Emissions:

The CO_2 emissions tests with the summer and winter B20 blends for both engines types resulted in decreased CO_2 exhaust emissions when compared with baseline petroleum diesel. As noted, the Rowan University research team estimated complete lifecycle greenhouse emissions of the blends tested ("Estimated Soy Biodiesel Greenhouse CO_2") and noted that NJ Transit may realize up to 9% and 23% emissions reductions for older (GP40FH-2) and newer (PL42-AC) engines, respectively[d]. The complete greenhouse gas-based life cycle analysis (field-to-wheels) of biodiesel should be considered when CO_2 emission reductions are calculated. In addition, the latest proven scientific data should be utilized when considering the direct and indirect land use effects from producing first generation biofuels. Direct land use change refers to the direct effects (i.e. effects on water sources and other measurable emissions) that occur during the production and usage of biofuels. Indirect land use change can be defined as the unintended release of greenhouse gas emissions due to land conversion around the world induced by utilization of existing croplands for production of feedstocks for first generation biofuels. For example, an indirect land use effect occurs when forest is converted to agricultural land when additional land is needed to grow biofuel feedstocks. Release of CO_2 into the atmosphere resulting from the clearing of forests must be accounted for in the overall biofuel greenhouse gas emissions analysis.

NOx Emissions:

The GP40FH-2 locomotive summer B20 tests exhibited increases in NOx (oxides of nitrogen) emissions of up to 14.9% when compared with baseline petroleum diesel. However, the same engine, when tested with winter B20 blends, exhibited NOx emissions decreases of up to 10%. The PL42-AC locomotive tests with summer B20 blends resulted in a decrease in NOx emissions of 15.5%. The same locomotive, when tested with winter B20 blends resulted in a decrease in NOx emissions of up to 17.8%

Previous studies performed with B20 in diesel engines suggest various results, although almost all of the earlier studies reported increases in NOx emissions when B20 emissions as compared to #2 petroleum diesel emissions. However, a minority of tests also showed a decrease in NOx emissions. National Renewable Energy Laboratory studies[1,2] state that NOx emissions can go up or down depending on diesel engine and test cycle. This matter is not well understood at this time, and more research is necessary.

HC Emissions:

Compared with baseline petroleum diesel, the GP40FH-2 locomotive tests resulted in increased HC (total unburned hydrocarbons) emissions for summer and winter ULSD B20 blends of 15% and 4.5%, respectively and ULSD (without B20) summer of 7.8%. The PL42-AC locomotive tests resulted in a decrease in HC emissions with summer blends of 6.8%. However, the same locomotive testing resulted in an increase in HC emissions of 12% -29% with winter blends.

The observed increase in HC emissions may be caused by several factors. One factor is the unknown effect on HC emissions of the high levels of kerosene in many winter blends necessary to meet NJ TRANSIT's 0°F cloud point requirement. Diesel fuel become cloudy when it begins to gel in cold temperatures, which reduces engine performance. The "cloud point" of a fuel is the temperature at which it becomes cloudy. The addition of kerosene to diesel fuel decreases the temperature at which the fuel begin to gel. The B20 winter blends contained as much as 56% kerosene. It is reported in previous literature that diesel fuel adulteration with kerosene increased tailpipe HC emissions.[3,4,5] For the GP40FH-2 locomotive, it was also found that the higher kerosene levels resulted in decreased horsepower, thereby decreasing the performance of the turbocharger, which possibly resulted in incomplete combustion and as mentioned above, increased CO emissions and slightly increased HC emissions. Both CO and HC presence would be indicative of incomplete combustion, which would be consistent with reduced turbocharger performance. Another factor is the fact that the instrument uncertainty for all hydrocarbon measurements are inherently higher than the other gaseous pollutant measurements performed by the analyzer because of the very low concentrations of HC compared to the other gaseous pollutants. The measured HC levels were on the order of 50 parts per million (ppm) and sometimes as low as 20 ppm, whereas the other pollutants levels were on the order of 1000ppm.

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[d] For a full discussion of the methodology used to calculate lifecycle greenhouse gas emissions, see the full report, *Rowan University, Evaluation of Emissions and Performance of NJ TRANSIT Diesel Locomotives with B20 Biodiesel Blends. Final Report: December 10, 2009.*

CO Emissions:

The GP40FH-2 locomotive exhibited decreases in total CO (carbon monoxide) mass emissions when tested with summer B20 blends when compared with baseline petroleum diesel . When the same engine is tested with winter B20 blends, the results showed an increase in CO emissions. The PL42-AC locomotive tests with summer and winter B20 blends result in a decrease in CO emissions. Several previous studies also suggest CO emissions reductions when diesel engines are tested with B20 Blends.[6,7,8] It is reported in the literature that cold start tests would result in an increase in CO emissions.[3] The CO increase with a winter B20 test of the older category engine can be attributed to the incomplete combustion conditions, and this could be an experiment-specific or engine-specific finding.

Performance and fuel consumption

As shown in Figures one through three below, the findings of this study suggests that both the older (GP40FH-2) and newer (PL42-AC) engines can operate on B20 summer blends with no unacceptable loss in power production and no increase in fuel consumption. The GP40FH-2 and the PL42-AC can both also successfully operate on the B20 winter blends, and actually show an increase in horsepower.

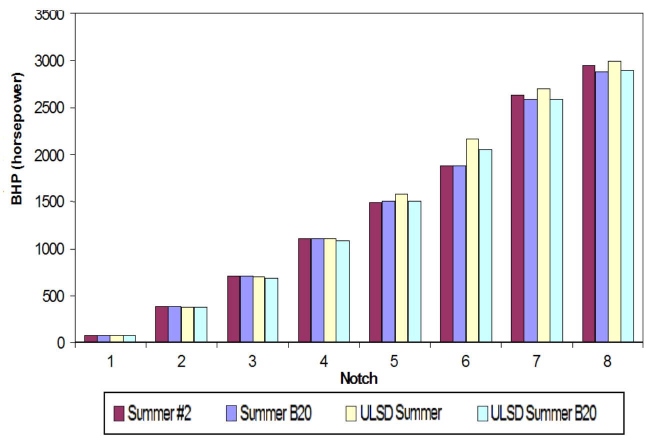

Figure 1: GP40FH-2 summer blends measurements.

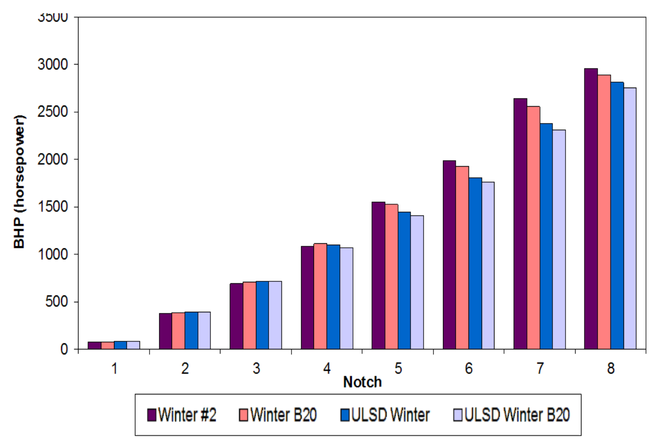

Figure 2: GP40FH-2 winter blends measurements.

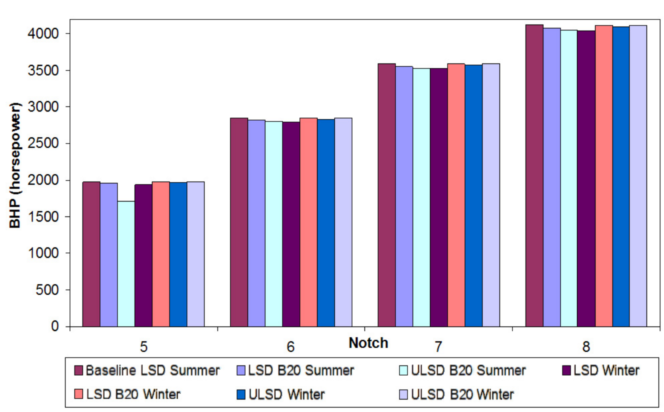

Figure 3: PL42-AC summer and winter blends measurements.

Exhaust Opacity

Exhaust opacity is an indicator of the amount of particulate matter in the exhaust, although there is not a direct correlation. Figures four through six below show that in both engine types, biodiesel summer blends resulted in reduction in exhaust opacity of up to 50% with respect to the #2 diesel baseline. This finding is also consistent with previous literature, which reported that B20 reduced exhaust opacity by 50% [9]. For the GP40FH-2, the biodiesel winter blends resulted in little variation in exhaust opacity with respect to the #2 diesel baseline, but the ULSD fuel actually exhibited slightly higher opacity than the baseline, which was unexpected. In the PL42-AC tests, the ULSD B20 winter blends exhibited slightly higher opacity than the ULSD or baseline LSD blends, which was an unexpected result.

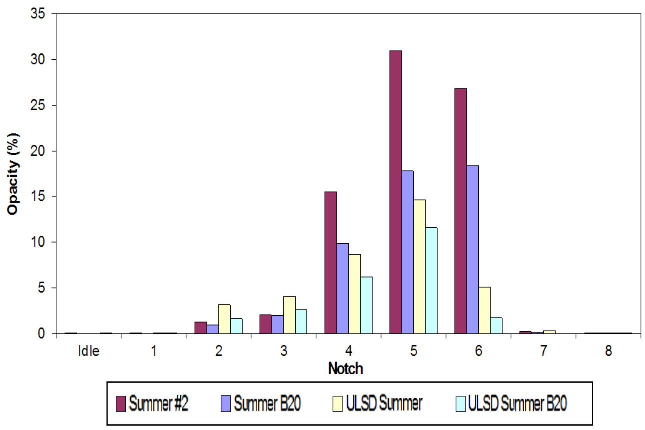

Figure 4: GP40FH-2 summer blends measurements.

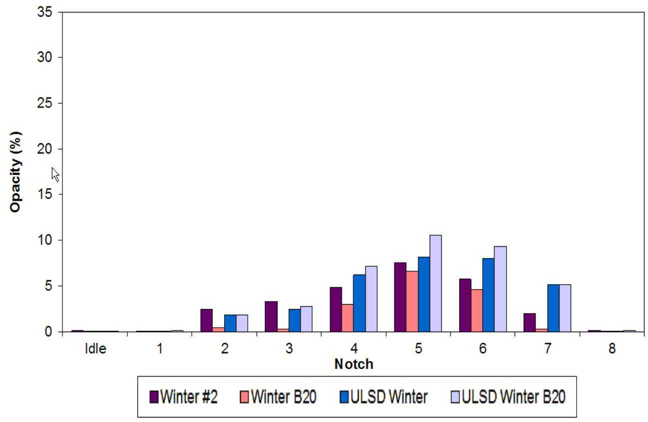

Figure 5: GP40FH-2 winter blends measurements.

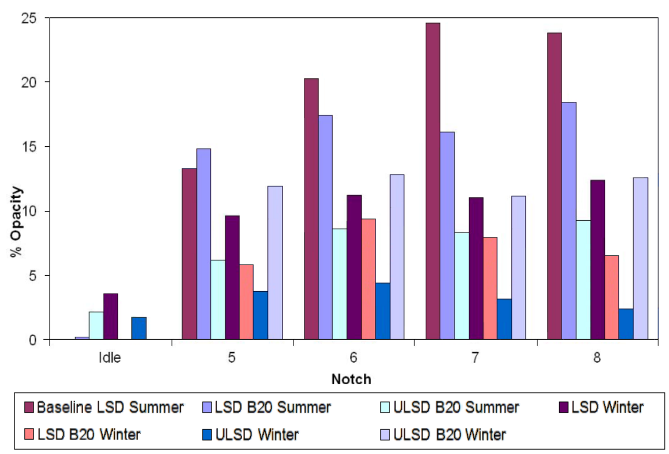

Figure 6: PL42-AC summer and winter blends measurements.

CONCLUSIONS

This study suggests that the use of B20 biodiesel-petroleum diesel blend in NJ TRANSIT commuter train locomotives could reduce the carbon footprint of the older trains by up to 9% and the newer trains by up to 23% without sacrificing engine performance or fuel efficiency. When tested in both the older and newer engine types in the NJ TRANSIT fleet, all four of the B20 blends in the study decreased carbon dioxide emissions with no impact on engine power or fuel consumption. Even when accounting for indirect land use changes, these preliminary results indicate that the use of B20 could reduce the level of greenhouse gas emissions attributable to NJ TRANSIT commuter train operations.

Although all of the B20 blends reduced carbon dioxide in both engine types, other pollutant measurements varied depending on engine type and seasonality. The only fuel that did not increase other pollutants was B20 summer blend when used in the newer engines. B20 summer blends reduced all of the tested pollutants when used in newer engines, but increased HCs and oxides of nitrogen (NOx) in older engines. B20 winter blends increased hydrocarbon (HC) emissions in both older and newer engines.

In the presence of sunlight, NOx and HCs undergo complex chemical reactions to produce ground-level ozone, which causes a variety of serious health and environmental effects. This study indicates that the use of B20 biodiesel blends in NJ TRANSIT commuter trains to reduce CO_2 would result in an increase in other air pollutants, and therefore may increase local air toxics impacts.

References

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